National Aeronautics and Space Administration

Connecting Projects to Complete the In Situ Resource Utilization Paradigm

Presented at the Joint
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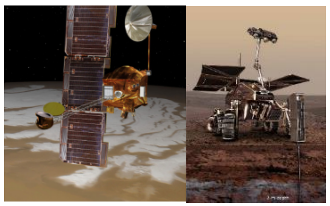
What is *In Situ* Resource Utilization (ISRU)?

ISRU involves any hardware or operation that harnesses and utilizes ‘in-situ’ resources to create products and services for robotic and human exploration

Resource Assessment (Prospecting)

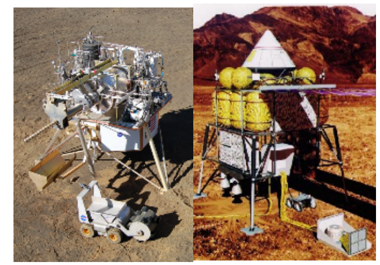


Assessment and mapping of physical, mineral, chemical, and water resources, terrain, geology, and environment

Resource Acquisition

Excavation, drilling, atmosphere collection, and preparation/ beneficiation before processing

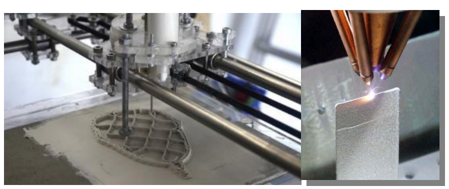
Resource Processing/ Consumable Production



Extraction and processing of resources into products with immediate use or as feedstock for construction & manufacturing

- **Propellants, life support gases, fuel cell reactants, etc.**

In Situ Manufacturing



Production of replacement parts, complex products, machines, and integrated systems from feedstock derived from one or more processed resources

In Situ Construction

Civil engineering, infrastructure emplacement and structure construction using materials produced from *in situ* resources

- **Radiation shields, landing pads, roads, berms, habitats, etc.**

In Situ Energy

Generation and storage of electrical, thermal, and chemical energy with *in situ* derived materials

- **Solar arrays, thermal storage and energy, chemical batteries, etc.**

- **‘ISRU’ is a capability involving multiple elements to achieve final products** (mobility, product storage and delivery, power, crew and/or robotic maintenance, etc.)
- **‘ISRU’ does not exist on its own.** By definition it must connect and tie to users/customers of ISRU products and services

ISRU Functional Breakdown

ISRU

Resource Assessment/ Prospecting

1.1 Site Imaging/Characterization
1.2 Physical Property Evaluation
1.3 Atmosphere/Gas Resource Evaluation
1.4 Mineral/Chemical Resource Evaluation
1.5 Volatile Resource Evaluation
1.6 Data Fusion, Analysis, Mapping & Monitoring

Resource Acquisition

2.1 In Situ Atmosphere/Gas Resources
2.2 Planetary Material Resources
2.3 Discarded Material/Trash Resources

Resource Processing/ Consumables

3.1 Extract/Produce Oxygen
3.2 Extract/Produce Fuel
3.3 Extract/Produce Water
3.4 Extract/Separate Gases for Life support/Science
3.5 Extract/Produce Manufacturing Feedstock
3.6 Extract/Produce Construction Feedstock
3.7 Extract/Produce Food Production Feedstock

In Situ Construction

4.1 Area Clearing, Landing Pads, Roads
4.2 Excavation - Berms, Trenches, Burial
4.3 Structure/ Habitat Construction
4.4 Shielding Construction

Manufacturing with ISRU Feedstock

5.1 Manufacturing with In Situ derived Metal/Silicon
5.2 Manufacturing with In Situ derived Plastics
5.3 Manufacturing with In Situ Produced Ceramics
5.4 Manufacturing with Recovered/Recycled/Repurposed Materials

In Situ Energy

6.1 Use of In Situ Material for Thermal Energy Storage
6.2 Use of In Situ Material for Electrical Energy Storage
6.3 In Situ Solar Array Production

Three Layers of Development: Concept/Technology Feasibility TRL 1-3
Subsystem/System Dev. in Relevant Environment: TRL 4-6
Flight Development

Three Primary Destinations: Moon Surface
Mars Surface
Asteroids/Mars Moons

Recent ISRU Related Development within NASA

ISRU

Resource Assessment/ Prospecting

- 1.1 Site Imaging/Characterizatio n
- 1.2 Physical Property Evaluation
- 1.3 Atmosphere/Gas Resource Evaluation
- 1.4 Mineral/Chemical Resource Evaluation
- 1.5 Volatile Resource Evaluation
- 1.6 Data Fusion, Analysis, Mapping & Monitoring

TRL 1-3 | TRL 4-6 | Flight Dev

Moon | Mars | NEAs

Resource Acquisition

- 2.1 In Situ Atmosphere/Gas Resources
- 2.2 Planetary Material Resources
- 2.3 Discarded Material/Trash Resources

TRL 1-3 | TRL 4-6 | Flight Dev

Mars | NEAs

Resource Processing/ Consumables

- 3.1 Extract/Produce Oxygen
- 3.2 Extract/Produce Fuel
- 3.3 Extract/Produce Water
- 3.4 Extract/Separate Gases for Life support/Science
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TRL 1-3 | TRL 4-6 | Flight Dev

Moon | Mars

In Situ Construction

- 4.1 Area Clearing, Landing Pads, Roads
- 4.2 Excavation - Berms, Trenches, Burial
- 4.3 Structure/ Habitat Construction
- 4.4 Shielding Construction

TRL 1-3

Moon | Mars

Manufacturing with ISRU Feedstock

- 5.1 Manufacturing with In Situ Regolith/ Metal/Silicon
- 5.2 Manufacturing with In Situ derived Plastics
- 5.3 Manufacturing with In Situ Produced Ceramics
- 5.4 Manufacturing with Recovered/Recycled/R epurposed Materials

TRL 1-3 | TRL 4-6 | Flight Dev

Moon | Mars | ISS

In Situ Energy

- 6.1 Use of In Situ Material for Thermal Energy Storage
- 6.2 Use of In Situ Material for Electrical Energy Storage
- 6.3 In Situ Solar Array Production

Where Does ISRU Work Reside in NASA?

NASA Headquarters

Human Exploration & Operations Mission Directorate

Advanced Exploration Systems Division

- ISRU Technology
- MOXIE
- Resource Prospector
- Lander Technology
- Logistics Reduction
- Synthetic Biology
- In-Space Manufacturing

- Autonomous Systems & Operations
- Modular Power Systems
- Life Support Systems
- Avionics and Software

MOXIE = Mars Oxygen ISRU Experiment

Space Technology Mission Directorate

STRG

- NSTRF/ECF/ESI

SBIR / STTR

Center Innovation Fund

Game Changing Development

- ISRU
- MOXIE
- Advanced Manufacturing

- Robotics
- Power and Energy Storage
- Advanced Manufacturing

STRG = Space Technology Research Grants
SBIR = Small Business Innovation Research
STTR = Small Business Technology Transfer
NSTRF = NASA Space Technology Research Fellowships
ESC = Early Career Fellowship
ESI = Early Stage Initiative

Science Mission Directorate

- ROSES

Planetary Science Division

- Mars 2020

- PICASSO
- MatISSE
- SSERVI
- Orbital and surface missions

ROSES = Research Opportunities in Space and Earth Sciences
PICASSO = Planetary Instrument Concepts for the Advancement of Solar System Observations
MatISSE = Maturation of Instruments for Solar System Exploration
SSERVI = Solar System Exploration Research Virtual Institute

Where Does ISRU-Related Work Reside in NASA? (Projects/Programs)

ISRU

- **Resource Assessment/ Prospecting**
- **Resource Acquisition**
- **Resource Processing/ Consumables**
- ***In Situ* Construction**
- **Manufacturing with ISRU Feedstock**
- ***In Situ* Energy**

Human Exploration and Operations Mission Directorate (HEOMD)

- Resource Prospector
- Cubesats

- ISRU Technology
- MOXIE

- ISRU Technology
- MOXIE
- Logistics Reduction
- Synthetic Biology

- Synthetic Biology

- In Space Manufacturing

Space Technology Mission Directorate (STMD)

- ISRU
- MOXIE
- SBIR/STTR
- NSTRF/ECF/ESI
- CIF

- ISRU
- MOXIE
- SBIR/STTR
- NSTRF/ECF/ESI
- CIF

- Advanced Construction using Mobile Equipment (ACME)
- 3D-Printed Habitat Challenge
- CIF

Science Mission Directorate

- ROSES
- SSERVI
- Surface Missions: Moon, Mars, NEAs

- ROSES

ISRU Capabilities Requires Information and Hardware from Other Projects

ISRU

- Resource Assessment/ Prospecting
- Resource Acquisition
- Resource Processing/ Consumables
- *In Situ* Construction
- Manufacturing with ISRU Feedstock
- *In Situ* Energy

Human Exploration and Operations Mission Directorate (HEOMD)

- Life Support Systems
- Life Support Systems
- Lander Technology
- Modular Power Systems
- Autonomous Systems & Operations
- Avionics and Software

Space Technology Mission Directorate (STMD)

- Propulsion (Cryo)
- Lightweight Structures and Manufacturing
- Autonomy and Space Robotic Systems
- Solar Array with Storage

Science Mission Directorate

- Resource Instruments
- Resource Physical Data
- Resource Physical, Mineral, & Volatile Data
- Resource Physical & Mineral Data
- Resource Physical & Mineral Data

On-Going ISRU Related Work By Project/Program

ISRU Capabilities and Areas of Development	Resource Propsector	AES/STMD ISRU	MOXIE	Synthetic Biology	In Space Manufacturing	ACME	Logistics Reduction	Life Support Systems
1.0 Resource Assessment / Prospecting								
1.1 Site Imaging/Characterization	X							
1.2 Physical Property Evaluation	X							
1.3 Atmosphere/Gas Resource Evaluation								
1.4 Mineral/Chemical Resource Evaluation	X							
1.5 Volatile Resource Evaluation	X							
1.6 Data Fusion, Analysis, Mapping, and Monitoring	X							
2.0 Resource Acquisition								
2.1 In Situ Atmosphere/Gas Resources								
2.1.1 Dust Filtration		X	X					X
2.1.2 Gas Constituent Separation & Capture		X	X					X
2.1.3 Gas Constituent Compression/Recycling		X	X					X
2.2 Planetary Material Resources								
2.2.1 Granular Mat'l Excavation		X						
2.2.2 Consolidated Mat'l Excavation		X						
2.2.3 Icy-Soil Drilling -Excavation		X						
2.2.4 Consolidated Material Preparation		X						
2.2.5 Material Transfer		X						
2.3 Discarded Material/ trash resources							X	
3.0 Resource Processing - Consumable Production								
3.1 Extract/Produce Oxygen								
3.1.1 Gas/Solid Processing Reactors							X	
3.1.2 Liquid/Solid Processing Reactors								
3.1.3 Gas/Liquid or Molten Processing Reactors								
3.1.4 Gas/Gas Processing Reactors		X	X				X	X
3.1.5 Biological Processing Reactors				X				
3.1.6 Water Processing		X		X				X
3.1.6 Product-Reactant Separation-Recycling		X		X			X	X

ISRU Capabilities and Areas of Development	Resource Propsector	AES/STMD ISRU	MOXIE	Synthetic Biology	In Space Manufacturing	ACME	Logistics Reduction	Life Support Systems
3.0 Resource Processing - Consumable Production								
3.2 Extract/Produce Fuel								
3.2.1 Gas/Gas Processing Reactors		X						X
3.2.2 Biological Processing Reactors				X				X
3.2.3 Water Processing		X						X
3.2.4 Product-Reactant Separation-Recycling		X						X
3.3 Extract/Produce Water								
3.3.1 Gas/Solid Processing Reactors		X						X
3.3.2 Product-Reactant Separation		X						X
3.3.3 Contaminant Removal		X						X
3.4 Extract/Separate Gases for Life support/Science								
3.5 Extract/Produce Manufacturing Feedstock				X	X			
3.6 Extract/Produce Construction Feedstock				X		X		
3.7 Extract/Produce Food Production Feedstock				X				
4.0 In Situ Construction								
4.1 Area Clearing, Landing Pads, Roads						X		
4.2 Excavation - Berms, Trenches, Burial								
4.3 Structure/Habitat Construction						X		
4.4 Shielding Construction						X		
5.0 In Situ Manufacturing								
5.1 Manufacturing with In Situ derived Metal/Silicon								
5.2 Manuafacturing with In Situ derived Plastics								
5.3 Manufacturing with In Situ Produced Ceramics								
5.4 Manuafacturing with Recovered/Recycled/Repurposed Materials					X			
6.0 In Situ Energy								
6.1 Use of in situ material for Thermal Energy Storage								
6.2 Use of In Situ materials for Electrical Energy Storage								
6.3 In Situ Solar Array Production								

Resource Prospecting

Resource Assessment (Prospecting) – What Does ISRU Need to Know?

- **Terrain**
  - Identify specifics such as slope, rockiness, traction parameters
  - Identify what part of ISRU needs each
- **Physical / Geotechnical**
  - Hardness, density, cohesion, etc.
  - Identify what part of ISRU needs each (e.g., excavation needs to know hardness, density; soil processing needs to know density, cohesion; etc.)
- **Mineral**
  - Identify specifics
  - Identify what part of ISRU needs each
- **Volatile**
  - Identify specifics
  - Identify what part of ISRU needs each
- **Atmosphere**
  - Identify specifics
  - Identify what part of ISRU needs each
- **Environment**
  - Identify specifics
  - Identify what part of ISRU needs each

Site Characterization and Resource Prospecting on Moon/Mars

Mission	Site & Terrain Properties	Dust Properties	Physical/Geotechnical Properties	Subsurface Properties (Indirect Volatiles)	Mineral Characterization	Volatile Characterization
Mars Excursion Rover (MER)	PanCam; Navcam	Magnets	Rock Abrasion Tool (RAT) Microscopic Imager (IM)		Minature Thermal Emission Spec (Mini-TES) Mossbauer Spec (MIMOS II) Alpha particle X-ray spec (APXS)	
Curiosity Rover	Mastcam		Drill/Sieves - Scoop Mars Hand Lens Imager (MAHLI)	Dynamic Neutron Spec (DAN)	ChemCam - LIBS Alpha particle X-ray spec (APXS) X-Ray Diffraction/ Fluorescence (CheMin)	Sample Processing System (SAM) GC/Quadrupole MS Tunable Laser Spec (TLS)
Mars 2020 Rover	Mastcam-Z	Weather/dust measurement (MEDA)		Ground Penetrating Radar (RIMFAX)	X-Ray Fluorescence spec (PIXL) UV Laser-Raman & Luminescence (SHERLOC) SuperCam - LIBS, Raman, Fluorescence, Visible/ IR reflectance	
ExoMars Rover (ESA 2020)	PanCam		Drill (2 m) Close up Imager	Neutron spectrometer Ground Penetrating Radar	IR - mast (1.15-3.3 μm) VIS/IR (0.9-3.5 mm) IR borehole (0.4-2.2 mm) Raman Spectrometer	Sample Processing System GC/MS Laser Desorption-MS
Resource Prospector Rover	360° camera capability on Lander Sterio Camera on Rover		Drill (1 m sample) Measure while drilling Drill Camera	Neutron spectrometer	Near IR	OVEN GC/MS Near IR
Luna 27 (Russia/ESA 2025)	TV imaging	Dust measurements Measurements of plasma/neutrals	Possible arm/scoop Drill (2m) Direct thermal measurement Optical imaging	Seismic measurement Radio measurements of temperature	Neutron/gamma ray spec UV/Optical Imaging IR Spec	Sample Processing System GC/MS and Laser MS

IR = Infrared Spectrometer; VIS = Visiable Light Spectrometer; UV = UltraViolet Spectrometer; MS = Mass Spectrometer; GC = Gas Chromatograph
LIBS = Laser Induced Breakdown Spectroscophy; OVEN = Oxygen and Volatile Extraction Node

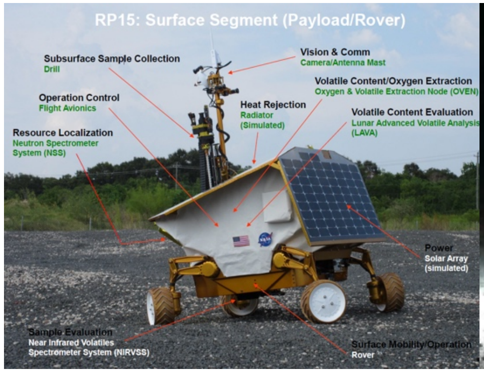
Site Characterization and Resource Prospecting on Asteroids/Comets

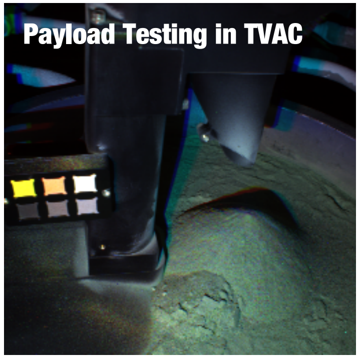
Mission	Site & Terrain Properties	Dust Properties	Physical/Geotechnical Properties	Subsurface Properties (Indirect Volatiles)	Mineral Characterization	Volatile Characterization
Hayabusa	Cameras Laser Altimeter (LIDAR) Multi-band Imager		Sampler - pellet impact Thermal sensors on Lander		X-Ray Fluorescence (XRF) Near IR Multi-band Imager	
Lander	Camera		Thermal sensors			
Hayabusa II	Cameras LIDAR Multi-band Imager		Sampler - pellet impact Small Carry-on Impactor (SCI)	SCI with Deployable camera	Thermal IR imager Near IR spectrometer Multi-band Imager	
Lander	Multispectral camera Descent imager	Hyperspectral IR microscope	Radiometer Magnetometer		Multispectral camera Hyperspectral IR microscope	
Dawn	Framing Camera Gravity Science-Radio			Neutron/Gamma Ray spec Sounding radar	Neutron/Gamma Ray spec Visible/Thermal IR spec	
OSIRIS-Rex	Camera- PolyCam LIDAR	SamCam	Sampler - pneumatic		X-Ray Fluorescence (XRF) Visible and IR spectrometer Thermal emission spec	MapCam
Rosetta	Optical imating	Atomic fource microscope Grain impact analyzer	Sounding Radar		Visible/IR thermal spec Optical and IR imager UV imaging spectrometer	Ion and neutral analysis MS Ion mass analyzer Microwave emission of volatiles
Lander	Lander imager	IR and visible analyzer	Harpoon and graplers Sampler, Drill, & Distribution (SD2)- down to 23 cm Magnetometer and plasma monitor		Alpha Particle X-Ray spec IR and visible analyzer	SD2 GC w/ isotope ratio MS

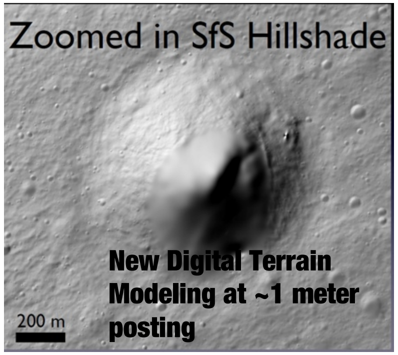
IR = Infrared Spectrometer; VIS = Visiable Light Spectrometer; UV = UltraViolet Spectrometer; MS = Mass Spectrometer; GC = Gas Chromatograph; LIDAR = Light Detection and Ranging

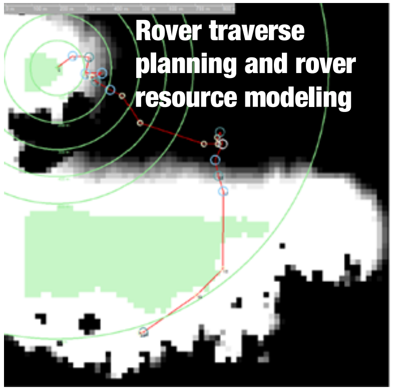
Resource Prospector

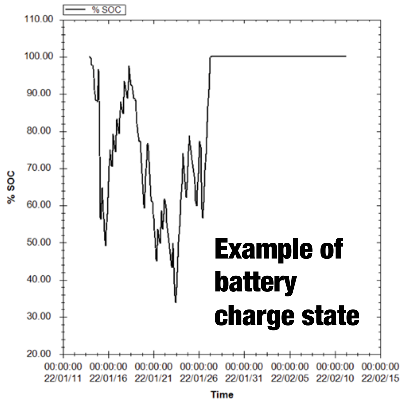
- **Resource Characterization**
  - What: Develop an instrument suite to locate and evaluate the physical, mineral, and volatile resources at the lunar poles
    - Neutron Spectrometer & Near Infrared (IR) to locate subsurface hydrogen/surface water
    - Near IR for mineral identification
    - Auger drill for sample removal down to 1 m
    - Oven with Gas Chromatograph/Mass Spectrometer to quantify volatiles present
  - ISRU relevance: Water/volatile resource characterization and subsurface material access/removal
- **Site Evaluation & Resource Mapping**
  - What: Develop and utilize new data products and tools for evaluating potential exploration sites for selection and overlay mission data to map terrain, environment, and resource information
    - e.g., New techniques applied to generate Digital Elevation Map (DEMs) at native scale of images (~1m/pxl)
  - ISRU relevance: Resource mapping and estimation with terrain and environment information is needed for extraction planning
- **Mission Planning and Operations**
  - What: Develop and utilize tools and procedures for planning mission operations and real time changes
    - Planning tools include detailed engineering models (e.g., power and data) of surface segment systems allows evaluation of designs
  - ISRU relevance: Allows for iterative engineering as a function of environment and hardware performance







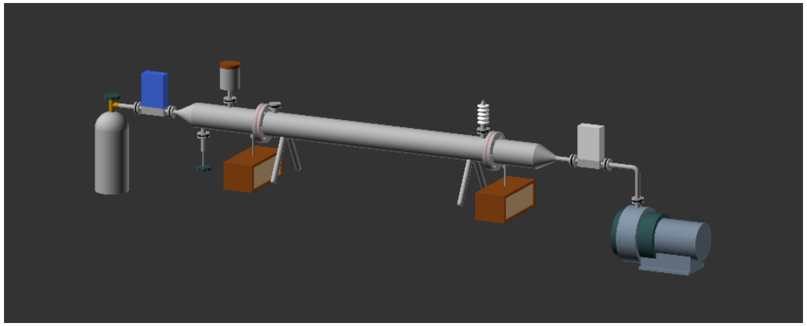




Resource Acquisition

Resource Acquisition – Dust Filtration / Mitigation

- **Electrostatic precipitator (STMD)**
  - Assembling components for 2nd generation flow-through precipitator prototype
    - Can vary diameter with three interchangeable tubes (80, 100, 160 mm)
    - Will investigate varying inner electrode diameter (wires to rods) and different electrode materials
  - Physics-based model to optimize geometry
    - Modeling equations of motion of particles entering device
- **Media filter**
  - Physics-based model for scroll media filter
  - Use existing data for validation
    - Mars flow loop, MOXIE
  - Working with MOXIE team for filter analysis and dust loading measurement technique
  - Designing full-scale media filter component for fabrication and testing in FY18



Electrostatic Precipitator Design

Initial set-up of electrostatic precipitator in a flow-through test

Scroll filter designed for Space Station

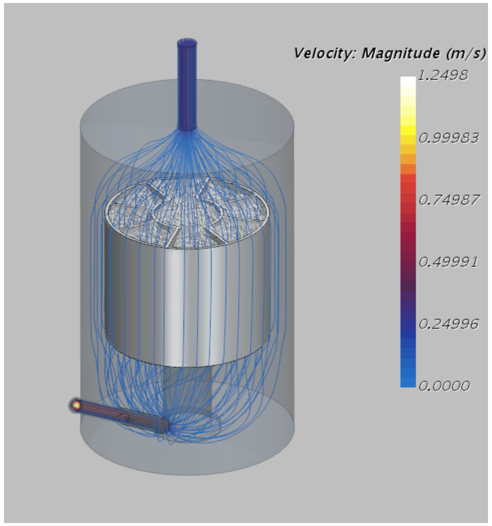
Resource Acquisition – CO_2 Compression

CO_2 Freezer Pump

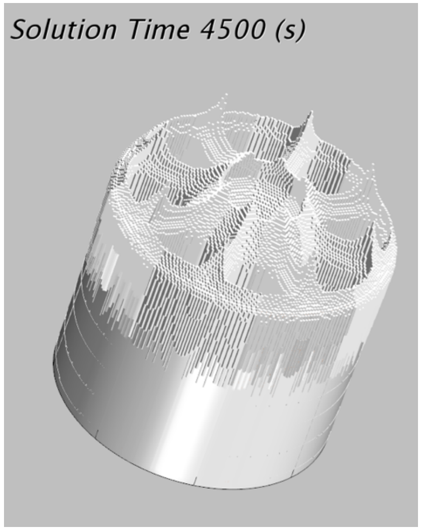
- **Analyzing different cold head designs**
  - Finite element modeling of flow and freezing
    - Compare to existing experimental data and iterate
  - Predicted CO_2 solid mass matches experimental results
- **Three 'ferris wheel' copper cold heads fabricated for testing**

Rapid Cycle Adsorption Pump

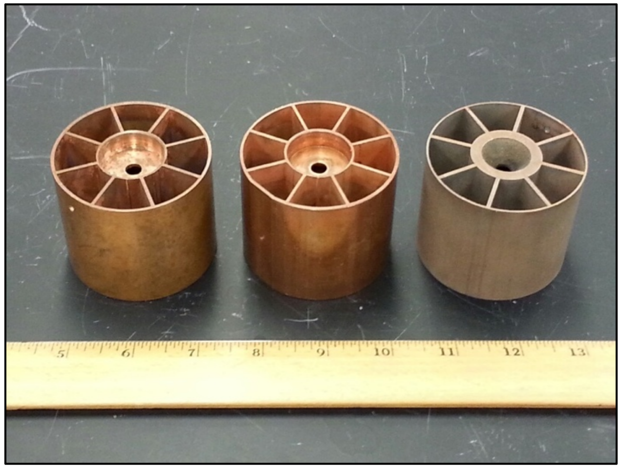
- **Developing Thermal Desktop / Sinda / Fluint model of microchannel rapid cycle sorption pump**
  - Sorbent (Zeolite 13X baseline) is contained in meso-channels
  - Fluid layers for rapid heating/cooling of adsorbent in microchannels
- **Addressing modeling / knowledge gaps to simulant Thermal-Swing Adsorption pump**
  - Toth and Langmuir 3-site isotherms coded into Sinda / Fluint
    - Adsorption rate, or kinetics, depend mostly on the isotherm
- **Design and analysis of realistic system for efficiently cycling temperature of adsorbent in 2 to 6 minute cycles**



Gas flow streamlines around cold head



CO_2 solid on cold head

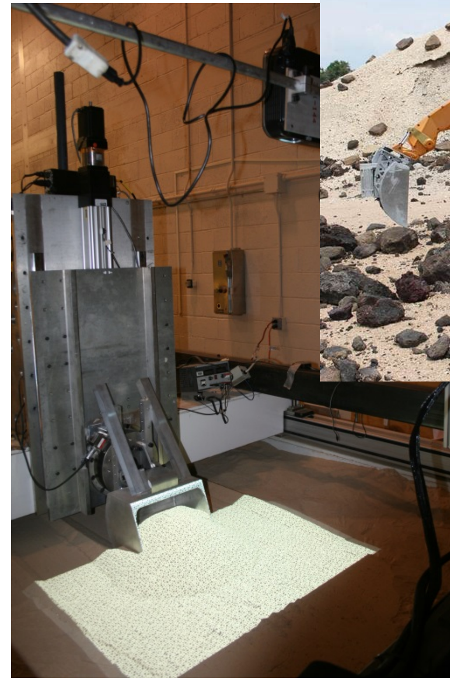


Three 'ferris wheel' copper cold heads for testing; one on right is 3D printed out of GRCop-84

Resource Acquisition – Excavation

- **Excavation modeling**
  - Update lunar excavation models to include excavation of different resource types
    - Mars low-water-content loose surface regolith
    - Mars hydrated minerals
    - Icy soils at Moon and Mars
    - Deep ice deposits on Mars
  - Validate with existing data and new data when available
- **Excavator design and architecture**
  - Use models to evaluate proposed excavation concepts and generate new concepts for mission architecture
  - Design, build, and test new and existing excavator concepts and test in relevant environment

Centaur 2 w/ APEX positioning of Badger percussive bucket



Excavation force determination with soil surface 3D measurement using structured light stereography

RASSOR (Regolith Advanced Surface Systems Operations Robot) excavator delivering loose soils

Resource Processing & Consumable Production

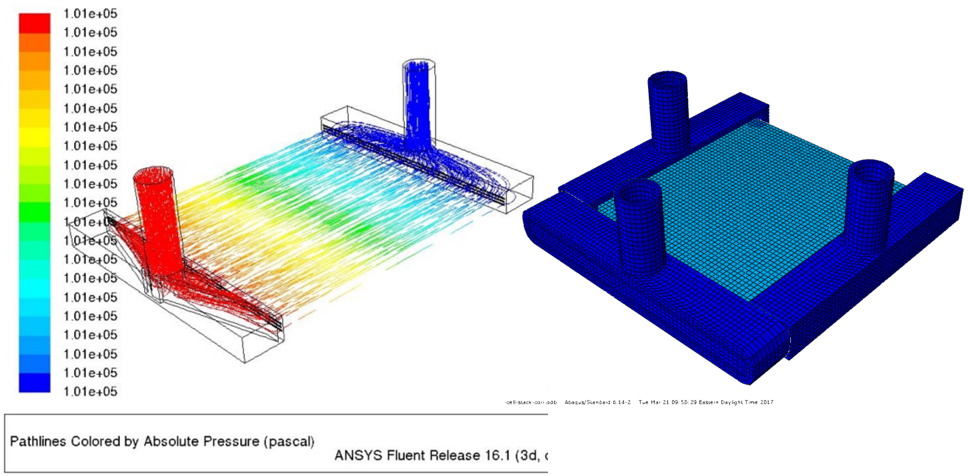
Resource Processing / Consumable Production

Solid Oxide Electrolysis (SOE) of CO_2

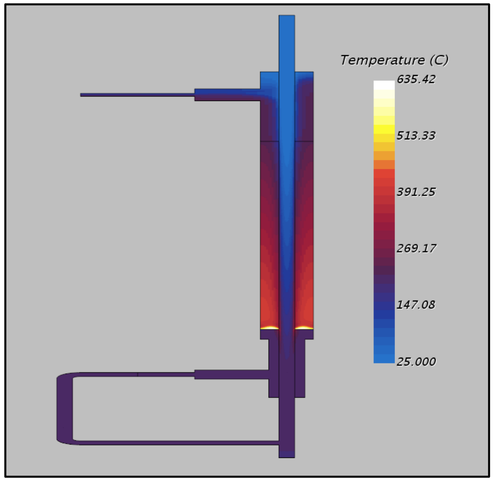
- **Baseline SOE stack and insulation model**
  - Gathering data for validation and improvements
  - Expanding and reformatting SOE physics-based performance model
  - Thermal insulation design model
- **GRC bi-supported cell fluid & mech. model**
  - Evaluate different manifold designs to improve gas distribution through stack
  - Identify stress points caused by thermal loads
  - Recommend design modifications to relieve critical stresses
  - Method will be applied to other SOE designs
- **SOE stack scaling limitations**
  - Use models to predict limits of active area per cell, # cells per stack

Sabatier Reactor for CH_4 Production

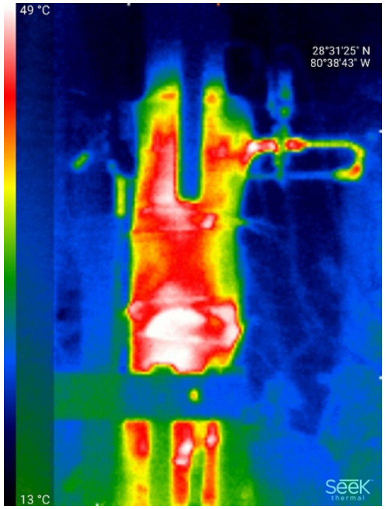
- **Sabatier reactor analytical model**
- **Reviewing state-of-the-art of conventional and microchannel reactor designs**
- **Catalyst pellets life investigation**
  - Analyze new and used catalyst pellets and identify nature of changes over time
  - Guide assessment of longevity/life challenges



Fluid and mechanical modeling of GRC bi-supported 3-cell stack. (left) pathlines colored by pressure; (right) mechanical stresses



Sabatier reactor thermal CFD model



Thermal camera image of Sabatier reactor during operation.

Resource Processing / Consumable Production

Open Reactor Concept

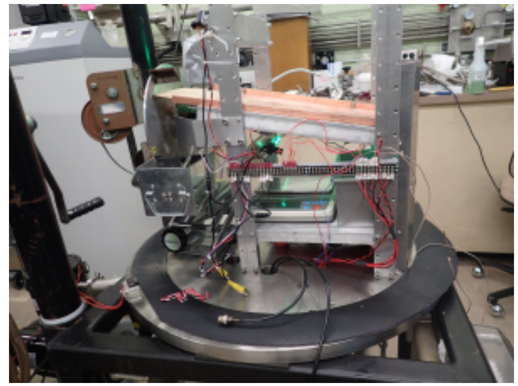
- **Open 'air' dryer concept testing completed at GRC**
  - Bucket wheel deposits soil on vibrating, heated plate
  - Fan blows Mars atmosphere over plate and sweeps liberated moisture into condenser
- **Tested with hydrated mineral, sodium tetraborate decahydrate (Borax), mixed in with GRC-3 simulant**
- **Physics-based model development**

Closed Reactor Concept

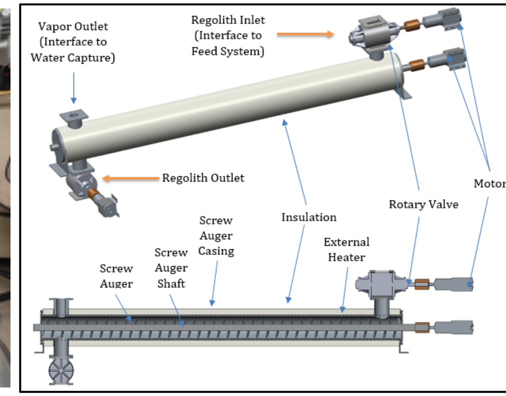
- **Auger-dryer concept based on terrestrial hardware**
  - Physics-based model to assess operation in Mars or lunar environment
- **Mars auger-dryer extraction hardware design**
  - Hardware to be tested in Mars environment chamber

In-Situ Extraction Concepts

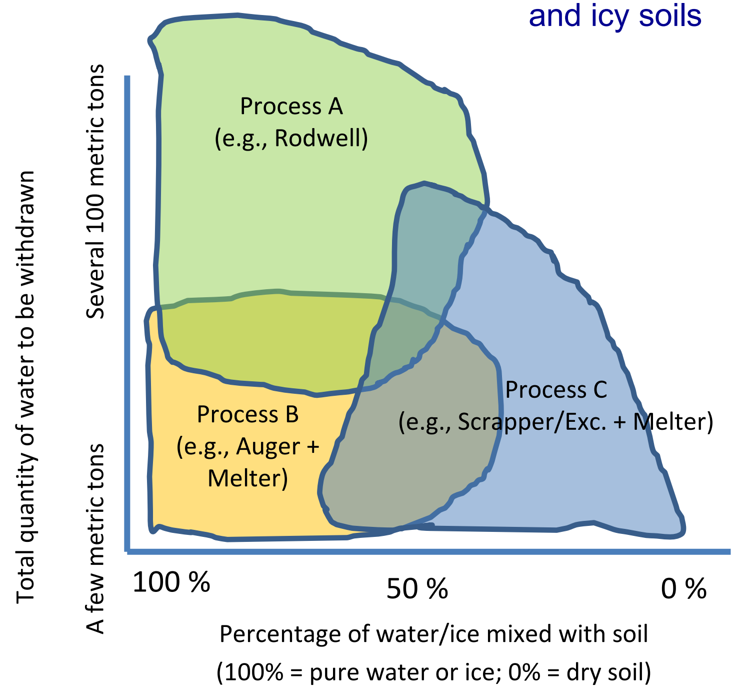
- **In-situ extraction modeling**
  - Extract the product at the resource location (process raw resource (ice) in place)
  - Working with analytical model developed for "Rodwell" on Earth to determine applicability to Mars (ice/soil mixtures, processing rates)



Open 'air' dryer at NASA GRC



Terrestrial auger soil dryer to be modeled for application to Mars and Lunar hydrated and icy soils

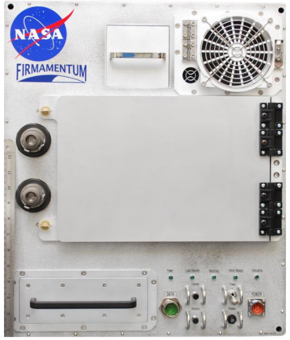


In Situ Manufacturing
&
In Situ Construction

In-Space Manufacturing (AES/GCD ISM Project)

- **In-Space Manufacturing & Repair Technologies**
  - What: Work with industry and academia to develop on-demand manufacturing and repair technologies for in-space applications.
    - Two polymer printers currently on ISS' Solicitation for 1st Gen. Multi-material 'FabLab' Rack capable of metallic and electronic manufacturing in-space released
  - ISRU relevance: These capabilities can use regolith and other in-situ materials for manufacturing & repair.
- **In-Space Recycling & Reuse**
  - What: Develop recycling capabilities to increase mission sustainability.
    - The Refabricator (integrated 3D Printer/Recycler) Tech. Demo. launching to ISS in early 2018.
  - ISRU relevance: In-situ materials and products can be recycled for reuse.
- **In-Space Manufacturing Design Database**
  - What: ISM is working with Exploration System Designers to develop the ISM database of parts/systems to be manufactured on spaceflight missions.
    - Includes material, verification, and design data. Information will be exported into Utilization Catalogue of parts for crew.
  - ISRU relevance: Database to include parts/systems manufactured using in-situ materials.

Additive Manufacturing Facility (AMF) on ISS developed via SBIRs with Made in Space, Inc.



ISS Refabricator (integrated 3D Printer/Recycler) developed via SBIRs with Tethers Unlimited, Inc.

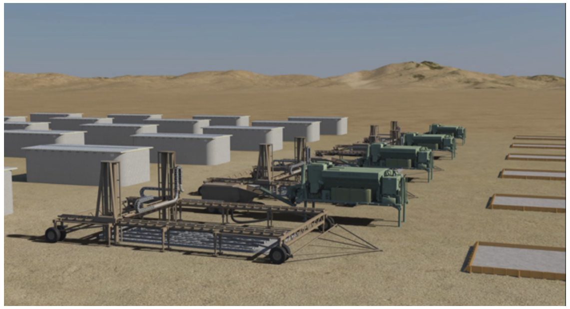
CT Scan (right) of compression cylinder manufactured on ISS (left).

Additive Construction with Mobile Emplacement (ACME) Automated Construction for Expeditionary Structures (ACES)

- **Additive Construction with Mobile Emplacement (ACME) (NASA STMD GCD)**
  - 2D and 3D printing on a large (structure) scale
    - Use in-situ resources as construction materials to help enable on-location surface exploration
  - Demonstrated fabrication of construction material using regolith simulant and multiple binders (polymers, cements)
  - Developing zero launch mass (ZLM) print head to extrude a mixture of regolith simulant and high density polyethylene through a heated nozzle
  - Use existing NASA GCD robots to position and follow tool paths with regolith print head end effector
- **Automated Construction for Expeditionary Structures (ACES) (U.S. Army Corps of Engineers)**
  - 3D print large structures to support deployment in remote areas
  - Dry Goods Delivery System provides continuous feedstock from in-situ materials
  - Liquid Goods Delivery System provides continuous flow of liquids/binders
  - Continuous Feedstock Mixing Delivery Subsystem combines all 'ingredients' and performs printing of structure

Standard 2-inch cube compression test specimens

ZLM print head demo illustration



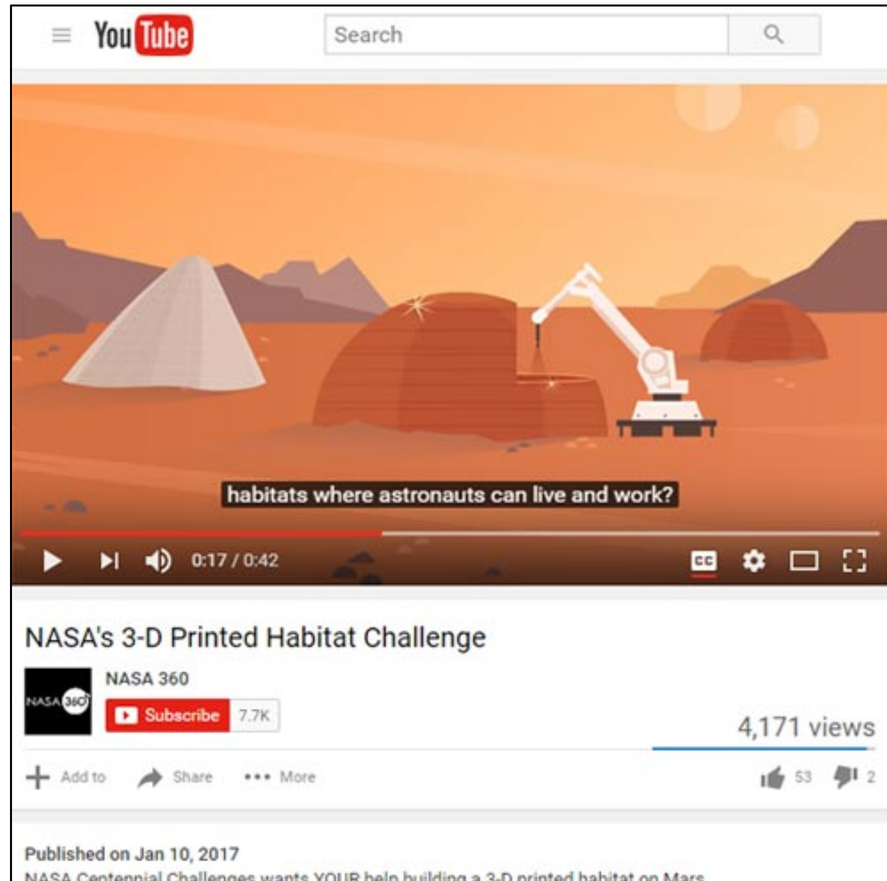
3D print 32' x 16' x 8' barracks with locally sourced concrete, within 48 hrs of deployment

Dry Goods Delivery System

NASA Centennial Challenge: 3D Printed Habitat

Goal: 3D Print a Habitat for Astronauts using Mars indigenous materials

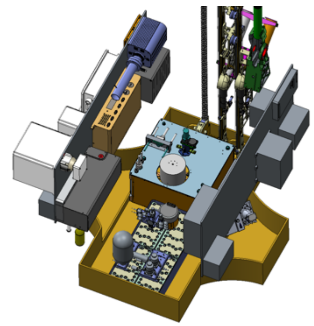
Prize: ***$1.4 million***



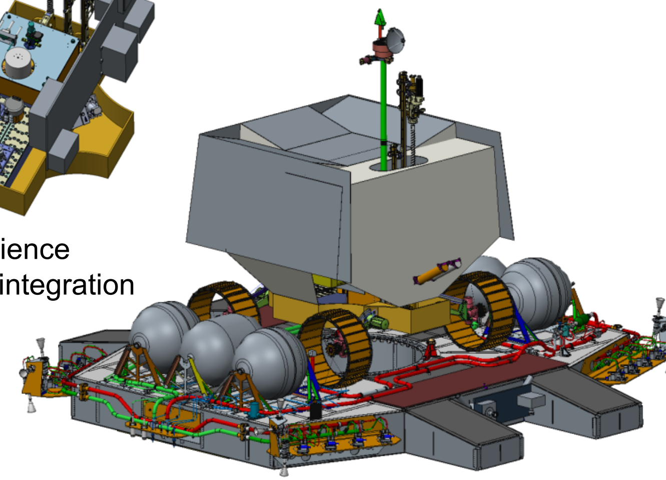
Synergistic Projects

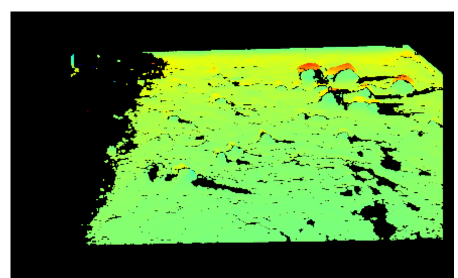
Game Changing Rover Technologies

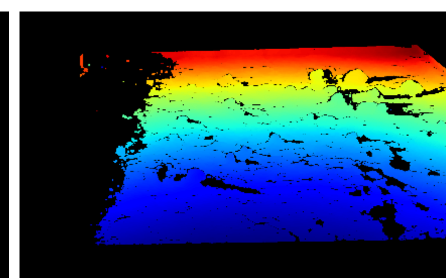
- **Advanced Mobility**
  - What: Advanced mobility including active suspension and explicit steering enabling soft soil traversal
    - Active suspension enables terrain traversal
    - Novel wheel, lost cost wheel design
    - Suspension/steering provides rover crawling behaviors
  - ISRU relevance: Provides access to lunar permanently shadowed regions for access to volatiles; robust rover mobility in all terrains for prospecting and excavation
- **Resource Prospector Mission integration**
  - What: Developing rover systems that move ISRU payloads around the lunar surface
    - Spectrometers, drills, regolith processing plants
  - ISRU relevance: Rover provides platform for hosting and moving ISRU instruments to target resource area
- **Rover Lunar Polar Localization and Navigation**
  - What: Evaluating ability to use stereo for localization and navigation at lunar poles
    - Both low contrast (all gray soil) and high dynamic range (dark shadows and bright sun)
    - Initial results indicate stereo will work at lunar pole
  - ISRU relevance: Understanding rover location is vital for prospecting, excavation, and delivery



Rover/Science package integration



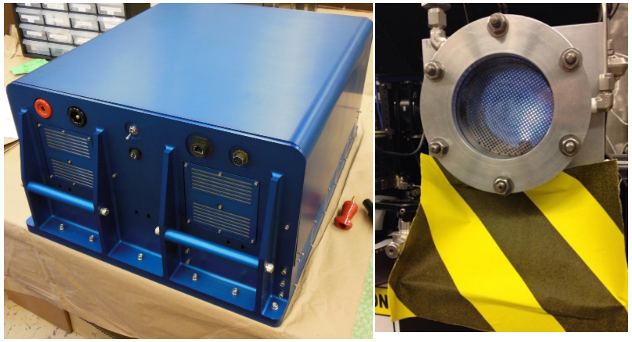




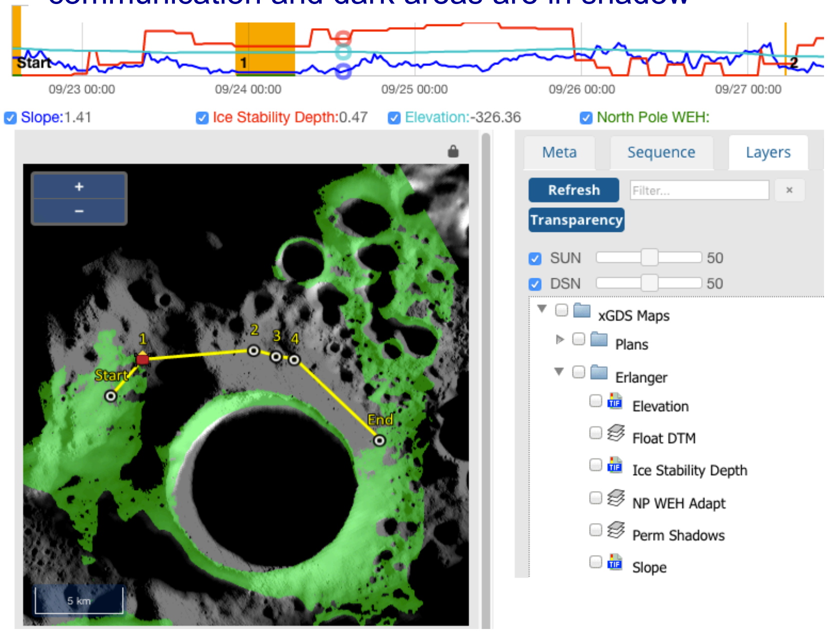
Autonomy (AES Autonomous Systems and Operations Project)

- **Autonomous Robotic Operations Planning**
  - What: Enhance existing tools for use during in-transit, orbital crewed missions
    - Fixed-based kinematics path-planning
  - ISRU relevance: Excavation and soil transport
- **Vehicle Systems Automation**
  - What: Integrate health management, scheduling and execution across vehicle systems
    - Ties together power and life support operations constraints
  - ISRU relevance: ISRU Sabatier and other components of processing plant
- **Robotic Mission Planning**
  - What: Mixed-initiative system that integrates traverse planning and activity planning
    - Planning with temporal, spatial, and spatial-temporal constraints
    - Managing duration uncertainty
  - ISRU relevance: excavation and soil transport

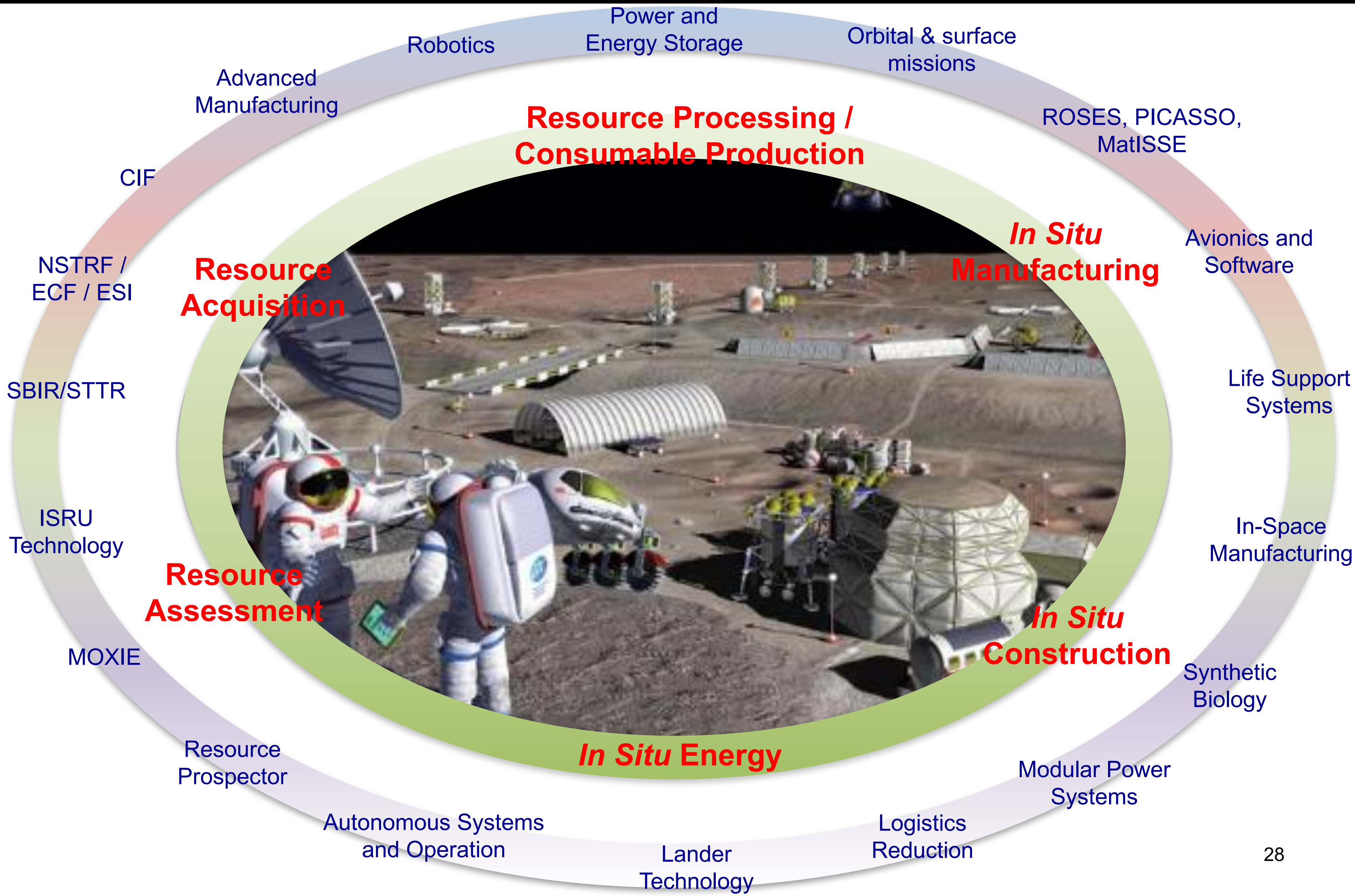
Vehicle Systems Automation: testing autonomy components integrated with flight software to operate hardware comparable to that needed for ISRU.



Robotic Mission Planning: Sunlight and communication layers in traverse planner; green areas have communication and dark areas are in shadow



Connecting Projects to Complete the ISRU Paradigm



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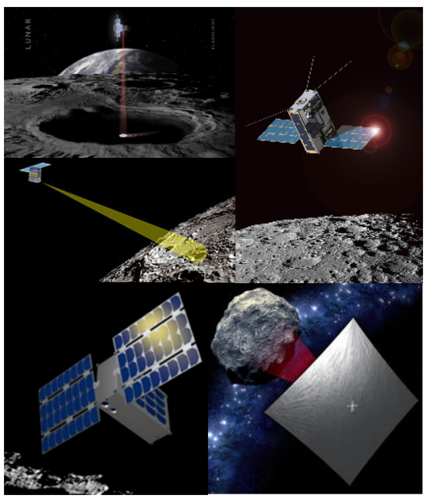
Back Up Charts

Current NASA ISRU Missions Under Development

Resource Prospector – RESOLVE Payload

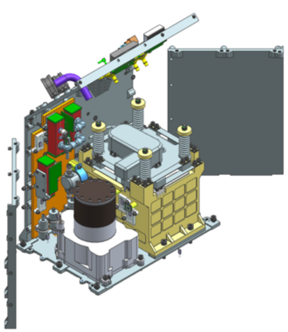
- Measure water (H_2O): Neutron spec, IR spec., GC/MS
- Measure volatiles – H_2, CO, CO_2, NH_3, CH_4, H_2S: GC/MS
- Possible mission in 2020



Cubesats (SLS EM-1 2018)

- Lunar Flashlight: Uses a Near IR laser and spectrometer to look into shadowed craters for volatiles
- Lunar IceCube: Carries the Broadband InfraRed Compact High Resolution Explorer Spectrometer (BIRCHES)

  LunaH-MAP: Carries two neutron spectrometers to produce maps of near-surface hydrogen (H)
- Skyfire: Uses spectroscopy and thermography for surface characterization
- NEA Scout: Uses a science-grade multispectral camera to learn about NEA rotation, regional morphology, regolith properties, spectral class



Mars 2020 ISRU Demo

- Make O_2 from Atm. CO_2: ~0.01 kg/hr O_2; 600 to 1000 W-hrs; 15 sols of operation
- Scroll Compressor and Solid Oxide Electrolysis technologies
- Payload on Mars 2020 rover

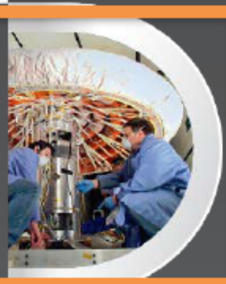
Space Technology Portfolio

Transformative & Crosscutting Technology Breakthroughs

Technology Demonstration Missions bridges the gap between early proof-of-concept tests and the final infusion of cost-effective, revolutionary technologies into successful NASA, government and commercial space missions.

Small Spacecraft Technology Program develops and demonstrates new capabilities employing the unique features of small spacecraft for science, exploration and space operations.

Game Changing Development seeks to identify and rapidly mature innovative/high impact capabilities and technologies that may lead to entirely new approaches for the Agency's broad array of future space missions.

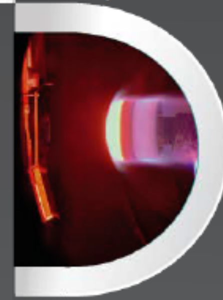


Pioneering Concepts/Developing Innovation Community

NASA Innovative Advanced Concepts (NIAC) nurtures visionary ideas that could transform future NASA missions with the creation of breakthroughs—radically better or entirely new aerospace concepts–while engaging America's innovators and entrepreneurs as partners in the journey.

Space Technology Research Grants seek to accelerate the development of "push" technologies to support the future space science and exploration needs through innovative efforts with high risk/high payoff while developing the next generation of innovators through grants and fellowships.

Center Innovation Fund stimulates and encourages creativity and innovation within the NASA Centers by addressing the technology needs of the Agency and the Nation. Funds are invested to each NASA Center to support emerging technologies and creative initiatives that leverage Center talent and capabilities.



Creating Markets & Growing Innovation Economy

Centennial Challenges directly engages nontraditional sources advancing technologies of value to NASA's missions and to the aerospace community. The program offers challenges set up as competitions that award prize money to the individuals or teams that achieve a specified technology challenge.

Flight Opportunities facilitates the progress of space technologies toward flight readiness status through testing in space-relevant environments. The program fosters development of the commercial reusable suborbital transportation industry.

Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Programs provide an opportunity for small, high technology companies and research institutions to develop key technologies addressing the Agency's needs and developing the Nation's innovation economy.